ASTRID: OPERATION PROCEDURES TO COMPLY WITH GRID REGULATION AND A PLANT LIFETIME UP TO 60 YEARS

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The GEN4 type ASTRID reactor acronym stands for Advanced Sodium Technological Reactor for Industrial Demonstration. Amongst its functional specifications there are two main items related to plant operation considerations: The ASTRID capability to accommodate the requirements of the French grid regulator and a reactor designed for a lifetime up to 60 years.

The French grid regulator requires that reactors not only have to participate to the grid frequency adjustment (which varies due to the whole grid production to consumption ratio balance) but also be able to switch to the house load operation whenever the regulator orders it.

Two options could be envisioned for the plant control: The first option deals with a regulation with the reactor power the second option would be an electric power modulation mastered by the tertiary circuit. For both options this paper presents the consequences expected on the plant control and safety criteria.

The second main item deals with a 60 years lifetime. This implies high level of cumulative mechanical stresses which are due to thermal loads from transients expected during the two main shutdown procedures: The emergency shutdown (SCRAM) and the rapid shutdown. This paper presents a study which has been performed to optimize the thermal load on main components.

I. INTRODUCTION

ASTRID will be the first prototype of the 4th generation nuclear reactor and as such it must meet the criteria from the forum GIF (Generation 4 International Forum) (Ref.1) whose major 4 are: increased level of safety, minimizing waste and proliferation by burning plutonium stocks, durability through optimizing natural resources and improved economic competitiveness by reducing investment and operating costs.

ASTRID prototype project was launched within the framework of the French law dated 28 June 2006 on the radioactive waste management. The chosen reactor type is a sodium fast reactor (SFR) due to the plutonium burner capacity of the fast neutron spectrum, the unique characteristics of sodium regarding the neutrons kinetic and its thermal capacity and finally by an important construction and operation feedback in France on SFR reactors such as Rapsody (1967-1983) Phenix (1973-2009) and Superphénix1 (1985-1998).

This paper presents two important ASTRID operating options which represent a significant contribution to the previously mentioned criteria:

1- The compliance with the electricity network safety regulations issued from the French electricity network company RTE that request to the main electricity producers (80% of electricity in France comes from nuclear power) both to ensure an adaptable power production in order to maintain the stability of the network frequency at 50 Hz and its self-sustaining capacity (house load) during a widespread incident on the network in order to replenish it rapidly.

For this mode called "network priority" and although the regulation does not impose to date the load following (day/night), on the horizon of ASTRID the plant must also be prepared for its demonstration. Indeed, the increasing part of the renewable energy sources (RES) with limited capacity to comply with network regulation (due to their intermittent feature) will naturally transfer this role to a permanent production source such as nuclear reactors (Fig. 1). Therefore it is predictable that load following becomes regulatory with increased amplitude level for the future nuclear industry.

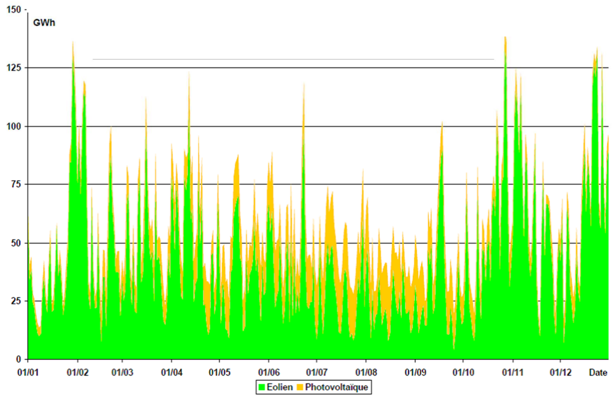

Fig. 1. Intermittence of production from RES (wind and solar) in France during 2013.

2- The other main operating option presented deals with the optimization of the shutdown procedures. The objective is to satisfy both reactor safety and a lifetime guarantee up to 60 years for non replaceable structures such as the internal vessel and the upper core structure. For other components such as primary pumps, intermediate heat exchangers and steam generators, their lifetime must be demonstrated up to 40 years with reliable data.

While mechanical calculations on structures are not yet completed with inelastic models, it is obvious that such long life duration still requires the operation to minimize thermal stresses during all shutdown type transients as well as reducing the number of occurrences counted for design.

The results of transients presented in this publication come from the system code CATHAR in which primary collectors are simple 0D volumes and homogeneous in temperature. A verification of the representativeness of this model regarding the thermal hydraulic heterogeneities has been carried out using a CFD code (STAR-CD).

The results presented in this publication is related to the Rankine thermodynamic cycle with vapor phase in the tertiary circuit.

II. GRID NETWORK REGULATION

French legal and regulatory applicable texts for production facilities are reported in (Ref.2 ; Ref.3). In addition, the European association of European Network Transmission System Operators (ENTSO-E), created in July 2009 has adopted the "Operation Handbook" booklet that includes an updated set of principles and rules for network operators transport in Europe (Ref.4).

From these requirements, the plant “house load” is regulatory together with the primary and secondary frequency control imposed for production facilities with output power higher than 120 MWe.

II.A. Load frequency control

The grid frequency varies depending on the balance between production and consumption and must therefore be continuously controlled and regulated. The frequency control keeps the grid frequency as close to the nominal value of 50 Hz required for proper operation of electrical systems of consumer processes. For that purpose, the main means of electric production must be flexible enough to lower or raise the power they supply to the grid. This power adjustment is divided into a primary control which represent a first adjustment required and in addition a secondary control with characteristics explained hereafter.

II.A.1. Requirements for the primary frequency control

In case of increase in the grid frequency, the power plant needs to reduce its power and be capable to reach any point of operation beyond a minimum plant power level Pmin and below the maximum plant power Pmax.

It corresponds to the ability to increase or decrease by 2.5% of the Pmax in less than 30 seconds, half in less than 15 seconds and be capable to maintain the new level for at least 15 minutes.

This setting (automatically controlled by the inner turbo-machine regulation) is used in priority for a network frequency deviation from 20 mHz to 200 mHz which is necessary on an average of 2 times per hour.

II.A.2. Requirements for the secondary frequency control

The secondary control of the frequency is complementary to the primary control and must be possible from any operating point between Pmin and Pmax.

The control must be possible within a band equal to +/- 4.5% of the Pmax with a gradient up to 9% Pmax in 133 second. The secondary control half band can be added to that of the primary control to provide a total reserve on the rise at least of 7% Pmax. The power plant must be able to contribute to the secondary control of the frequency by controlling its active power according to a control signal coming from RTE. The unit must have equipment capable of receiving the control signal and change its power supplied to the grid.

II.A.3. Frequency control by the neutronic power control

Regulatory power kinetics of around 5% Pmax/minute are more demanding for a SFR type compared to a PWR type because of the high thermal inertia due from the big volume of sodium in the collectors and in the secondary sodium loops. Therefore, considering a change of the outlet core temperature (following a change in neutronic power), the energy transfer to the steam generators and therefore to the turbine lead to an electric power output change performed with a significant time delay of several ten of seconds. With the conventional reactor control processes this transit time is not compatible with the requirement of 5% Pmax/minute. In order to ramp up the energy time transfer from the primary circuit to the tertiary circuit, a specific regulation of the thermal power extracted from the core to the turbine is required avoiding unstable thermohydraulic conditions. The principle is to regulate the outlet core temperature rather than neutron power itself while temporarily correcting the secondary loop flowrate to quickly adapt the power extracted from steam generators.

Figure 2 shows results of power extracted from the three different circuits and subject to a typical secondary frequency control ramp. (9% Pmax in 133 s). Results show the feasibility of the required power ramps:

- The neutron power that requires slightly passing the ramp to meet the outlet core temperature regulation.

- The power of the intermediate heat exchanger (IHx) which is a smoothed replica of the core power curve shifted in time.

- The power turbine that properly respects the regulatory power level.

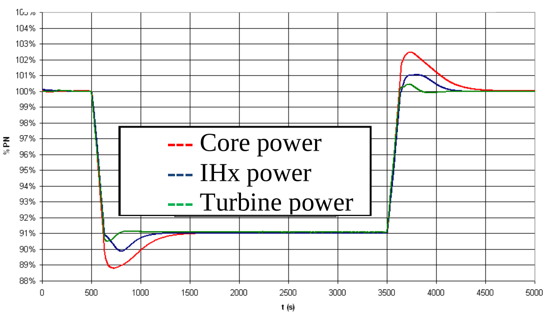

Fig. 2. Simulation of power transients during a secondary frequency control.

During this "network priority" mode, the core power regulation was chosen to be performed using three control rods from a total of 18. To validate this option and in accordance with the frequency control requirements, the operating range and the safety consequence of an unexpected regulation rods withdrawal (RIB) must be analyzed and the preliminary approach is presented below.

II.A.4. Operation range during the "frequency control" mode:

During this mode and as a first case of studies, the operating range submitted to the frequency control is set to [88.5% Pmax; 100% Pmax]. The nominal operation of the reactor is set at 93% Pmax to comply with the power reserve upward to 7% Pmax (cf. § II.A.2).

For the frequency control, the control rods management scheme is shown in Fig. 3 where 3 out from 18 rods (two bundles of 9 rods each) are used for the "frequency regulation" while the other 15 rods remain in a curtain mode are used to manage the fuel rods depletion during the operation cycle.

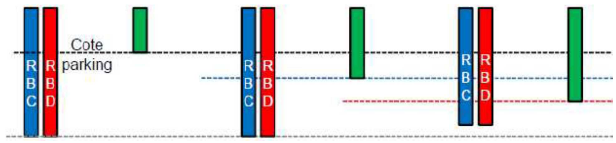

Fig. 3 : Control rods scheme during the "frequency control" mode.

The initial ramp to 100% Pn is performed with the 3 regulation rods in a "park" position. Then the three control rods are lowered setting the nominal core operating range to 93% Pmax. Finally, the 3 regulation rods are lowered with a margin to allow the regulation irrespective of the cycle time.

Preliminary analysis of this rod architecture shows that the necessary anti-reactivity is obtained to ensure the effective regulation unconditional on the operating range retained.

This estimation includes a cumulative margin which corresponds to:

- The loss of effectiveness over the cycle (control rod depletion, loss of control rod effectiveness depending on the rods elevation, the evolution of reactivity feed back)

- Uncertainty about the control rods speed

II.A.5. Some features about the unexpected regulation rods withdrawal (RIB)

The safety analysis approach in the case of RIB of the 3 regulation rods is based on the maximum reactivity insertion with uncertainties on the difference between the read and the true rods elevation. Conservatively, this uncertainty is the differential expansion of core-vessel-rods.

The consequences of a RIB have been assessed and are acceptable which do not call into question the design of the 3 regulation rods.

During the next phase of study the following investigations will be launched:

- Minimization of uncertainties through a more precise characterization of absorbent rods efficiencies, an optimized design of the rod mechanisms combined with instrumentation associated with the positioning.

- The I&C (Instrument & control) safety analysis for the transition phase between the two modes of operation: "network priority" or "reactor priority" with 18 rods.

II.A.6. The frequency control via the tertiary circuit:

The alternative to the frequency control through the core power could be a power reserve from the tertiary circuit.

The idea is to maintain the core power to 100% Pmax and supply the power reserve requested by the grid regulator to an external process which can comply with an intermittent supplying. Indeed, the power supplying to the process would be the difference between the core power (maintained at 100% Pmax permanent level) and the requested power to be delivered to the grid.

This split power can be carried out in two different modes:

- By deriving the tertiary fluid to supply a process requiring a high-temperature fluid with a return in the tertiary loop.
- By-pass of a portion of the electrical current directly from the turbine electric generator.

The first option is studied at a preliminary level either to supply thermal storage capacity that can be rendered to increase the hot spot of the thermohydraulic cycle or to produce a cold source to lower the cycle cold spot and thus for both cases increase the efficiency of the thermohydraulic cycle.

The second option was chosen as a priority in our studies. In the frame of future "smart grids", ASTRID could benefit from the development of new battery technology with a power converter and an associated control algorithm to master the electric storage. For now the scale of production is around 1 MWe for 30 minutes and would be suitable at first for the primary frequency control.

Another option considered is the provision of this diverted current to hydrogen production units that can accommodate such an intermittent electricity supply. Considering the high confidence on electrolysis technology development to withstand the regulatory needs, the studies rather focus on long term economy through expected hydrogen selling price compared to its production and transport cost. In addition, for security purposes the distance for hydrogen risk to local populations and sensitive nuclear installations are to be evaluated.

II.B. House load operation

The ability of ASTRID to perform a house load procedure must be demonstrated for two main reasons:

- It is regulatory for the network security in case of a major failure of the electricity transmission network that need immediate available power reserve to participate in its reconstruction.
- In case of a short duration loss of the plant supply voltage of about one second, the house load procedure is initiated to avoid a reactor shutdown procedure.

The house load procedure corresponds to an automatic power decrease (RAP) to 50% Pmax in order to quickly recover the full power. After inhibiting the core outlet temperature regulation, the control rods are inserted with an offset value to cover the cycle duration. In a short term, the primary flow is maintained to 100% and the secondary and tertiary flows are decreased to the 50% Pmax parameters in accordance with the values of the ASTRID load diagram.

In parallel the by-passing of the turbine with 40% of Pmax is carried out. Consequently the generator operates with a capacity of about 10% Pmax to self-supply the plant.

In a longer term (~ 1/2 h) the primary pumps are manually decreased to its value compatible with 50% Pmax and the core outlet temperature control is reestablished.

Preliminary studies show that during this procedure the shutdown protection limits are not met.

III. SHUTDOWN PROCEDURES

III.A. Introduction

The fast neutron reactors have two procedures for the reactor shutdown:

- The "scram" corresponds to the simultaneous release under gravity of all control rods. The "scram" is trigged by a safety protection consequently to initiating events that could lead to severe damages. This is an immediate stop (in about 2 seconds) of primary fission reactions and therefore only the residual power (due to the de-excitation of unstable nuclei) must imperatively be removed.
- The "rapid shutdown" is a slower stop compared to the "scram" with a motorized insertion of the control rods by few millimeters per second. The "rapid shutdown" is activated for initiating events not involving reactor safety but rather damages from the secondary or tertiary circuits that require a shutdown for diagnosis and repair.

Both types of shutdowns combined with their number of occurrences are of great importance in the design of hot structures. Indeed the thermal transients due to shutdowns are responsible of thermomechanical stresses leading to cumulative damages which determine the lifetime of ASTRID plant.

For safety reasons the requirement on "scram" procedure is to maintain the primary pump to its nominal value to avoid a core event while decreasing the cooling flowrate. This major requirement leads to an increase of thermal shocks on hot structures and therefore the "scram" procedures as well as the "rapid shutdown" must be redesigned with respect to the most thermal loaded internal structures of which (Fig. 3):

- The upper core structure
- The intermediate heat exchanger
- The inner vessel
- The steam generator

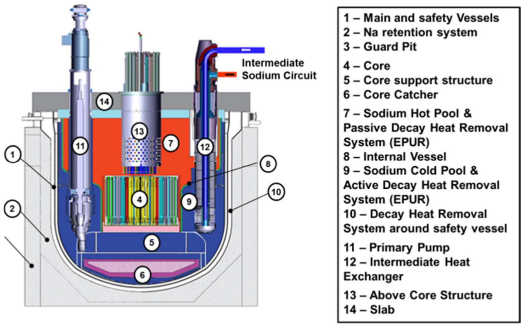

Fig. 3. Main components of the primary circuit

III.B. The "scram" procedure

The baseline scenario for the "scram procedure" is the following:

- Release under gravity of all control rods,
- Maintenance of primary flowrate to 100% ,
- Decrease of secondary flow from 100% to 25% nominal value,
- Regulation of the steam generator outlet sodium temperature from 345 °C to 320 °C by the tertiary feedwater flow.

The kinetic of the secondary flowrate decrease is the main parameter subjected to this optimization study.

The release of the control rods lead to a very rapid reduction in power and therefore a major cold thermal shock appears at the core outlet which directly impacts the upper core structure. For the three other components the shutdown optimization criteria are:

- Limiting the hot thermal shock of the IHx outlet (directly associated with the kinetic of secondary flow decrease) to limit the thermal load on the cold structures of the primary circuit (core support structure),

- The reduction or elimination of a thermal gradient inversion across the inner vessel (temperature in the hot collector lower than the temperature in the cold collector) in order to reduce the thermal stress on the vessel,

- Limiting the secondary circuit cooling slope to limit thermal stresses on IHx and steam generator components.

The parametric study is based on the duration of the secondary flow decrease from 100% to 25%. The durations tested are: 8 s, 50 s, 100 s, 150 s and finally 200 second.

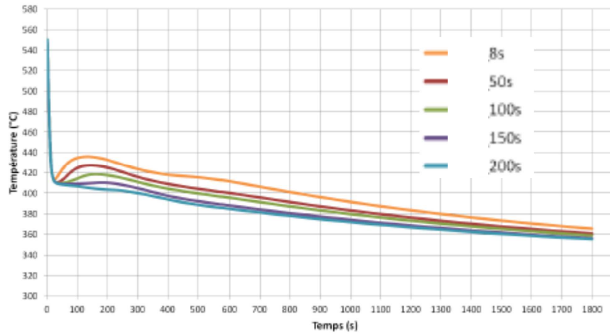

Fig. 4. Outlet core temperatures

Fig.4 shows the evolution of the average outlet core temperature with an initial cold shock of about 11 °C/s.

Whatever the decrease duration of the secondary flow, the initial thermal shock is the same. This is due to the proximity of the core outlet from the "upper core structure" that does not allow any optimization for this structure.

The subsequent phase shows a rise in the temperature which is directly related to the result of the behavior observed in the IHx outlet presented in Fig. 5. This rise vanishes from a secondary flowrate decrease kinetic equal to 150 seconds.

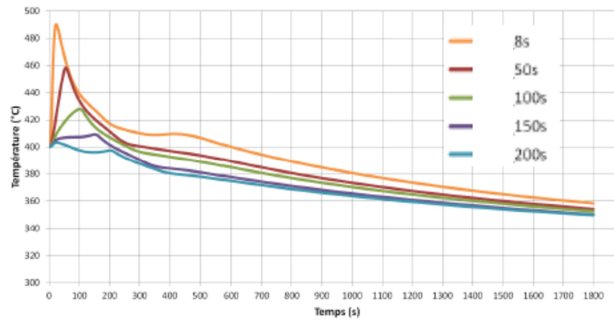

Fig. 5. Outlet IHx temperatures

A rapid kinetic of the secondary flow causes the appearance of a hot shock at the IHX outlet (Fig.5). The reason is that the primary rate being maintained at 100% , the secondary flow must be maintained longer to guarantee a sufficient level of heat exchange between the primary and secondary loop. The hot shock at the IHx outlet could highly impact the cold structures (core support structure, diagrid, primary pump, main vessel) and must be avoided with a secondary flowrate decrease kinetic from 150 seconds.

The second optimization criteria of the "scram" procedure is to avoid the inversion of the thermal gradient across the inner vessel. Fig.6 and Fig.7 show the average core and IHx outlet temperatures thus providing the maximum gradient through the inner vessel. Once again the secondary flowrate decrease kinetic of 150s illustrate the beneficial effect (Fig. 7).

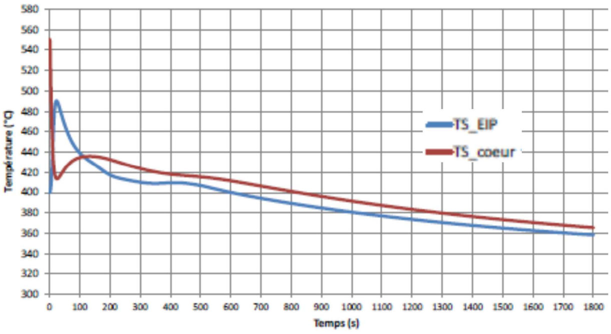

Fig. 6. Temperature gradient through the inner vessel for a secondary flowrate ramp of 8 s.

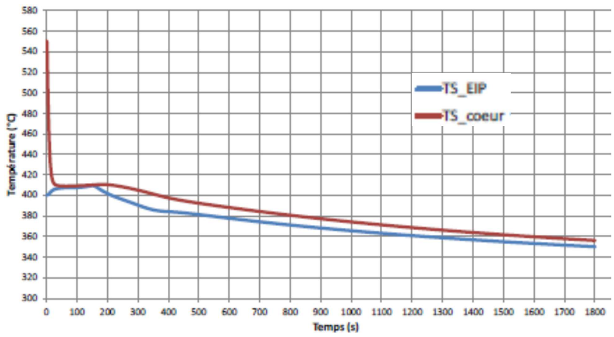

Fig. 7. Temperature gradient through the inner vessel for a secondary flowrate ramp of 150 s.

In conclusion of this analysis, the kinetic of the secondary flowrate decrease of 150s was chosen as the reference value for the "scram" procedure. Indeed, this option avoid the heat shock at the IHx primary loop outlet (criterion 1), eliminates the risk of inverse temperature gradient through the inner vessel (criterion 2) and limits the impact on the secondary loop components and on the steam generator (criterion 3).

III.C. The rapid shutdown procedure

The rapid shutdown procedure aims to anticipate reactor shutdown upon detection of events relating to secondary or tertiary circuits to avoid the penalty of the thermal shock due to the "scram" procedure. This anticipation should reduce the thermal loads that would be generated in the absence of such protection.

During the "rapid shutdown" procedure it is ensured that the speed of insertion of the control rods is fast enough to avoid the occurrence of significant differences related to the time of the cycle.

In the interest of procedures simplification, the optimization of the "rapid shutdown" is conducted to have the same secondary and tertiary flow decreasing kinetics as those used for the "scram procedure".

Compared to the "scram" procedure, the motorized insertion of the control rods leads to reduce the slope of the core outlet cold shock and thus the thermal loads on the upper core structures. For the other hot structures (IHx and inner vessel) the thermal gradients are quite similar to those of the "scram" shutdown.

In case of a "rapid shutdown" procedure the core outlet temperature transients are compared between the onset and the end of cycle. The comparison with the "scram" procedure transient is also presented (Fig.8).

This figure shows the benefit of the "rapid shutdown" on the maximum gradient imposed on the upper core structures. The core outlet shock is limited to 2-4 °C/s depending on the time of cycle.

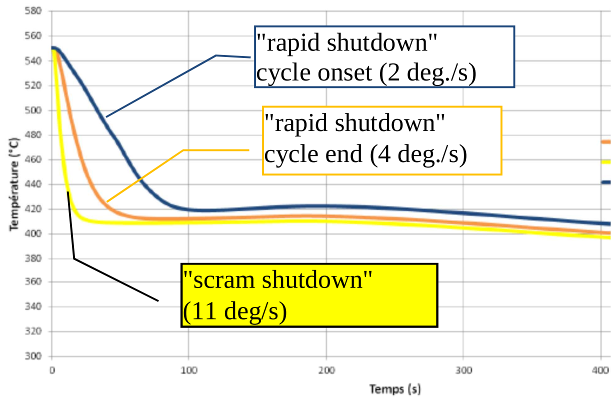

Fig.8 : Outlet core temperature for "scram" and "rapid" shutdown procedures"

III.D. Program studies to come

The transients related to the optimized shutdown procedures presented in this paper are new input data for the inelastic calculations on the primary circuit hot structures. ASTRID is now entering a "basic design" phase during which a high priority will be given to ensure that the structures will last the required lifetime of the reactor ASTRID (cf. § I).

Although the shutdown procedures are optimized the current calculations do not generate margins related to the mechanical damages on the upper core structures, the inner vessel and the IHx.

Several options will be studied to achieve this objective:

- Reduction of the total number of occurrences for the category 2 events leading to a shutdown procedure.

- Reconsidering the events consequences for which a "scram" procedure has been initially identified and could be protected by a "rapid" shutdown without penalizing reactor safety.

- Reducing uncertainties in defining the upper limits of operation as input data for the mechanical calculations.

- Taking into account the actual life at full power considering the intermediate cycles due to the prototype feature leading to a less average power output of ASTRID (balance of core phase, grid network regulation, experimental campaigns ...).

IV. CONCLUSIONS

The ASTRID project starts its basic design phase in 2016 and maintains its ambitious targets of an industrial demonstration prototype in order to establish the feasibility of a French SFR fleet on the horizon of the second half of the century. Among its specifications, two essential requirements for the future have been preliminary studied and presented in this paper:

- The feasibility of the network grid monitoring that will be essential for the nuclear industry because of its flexibility and availability in comparison to renewable energy which are much less able to meet the grid network security requirements.
- The optimization of the shutdown procedures for a better economy targeting a lifetime up to 60 years for non-replaceable structures.

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